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# Large electric-field induced electron drift velocity observed in an $In_xGa_{1-x}As$-based $p-i-n$ semiconductor nanostructure at $T=300$ K

W. Liang and K. T. Tsen[a]
*Department of Physics and Astronomy, Arizona State University, Tempe, Arizona 85287*

D. K. Ferry
*Department of Electrical Engineering, Arizona State University, Tempe, Arizona 85287*

Meng-Chyi Wu
*Department of Electrical Engineering, National Tsing-Hua University, Hsin-Chu 300 Taiwan, Republic of China*

Chong-Long Ho and Wen-Jeng Ho
*Telecommunication Laboratories, Chunghwa Telecom Co., Ltd., Taoyuan 326 Taiwan, Republic of China*

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Transient subpicosecond Raman spectroscopy has been used to measure electron transport properties in an $In_xGa_{1-x}As$-based semiconductor nanostructure under the application of an electric field. The deduced electron drift velocity has been found to be significantly larger than either GaAs or InP-based $p-i-n$ nanostructures under similar experimental conditions. We attribute this finding to both the smaller electron effective mass and the larger $\Gamma$ to $L\,(X)$ energy separations in $In_xGa_{1-x}As$. The experimental results are compared with ensemble Monte Carlo calculations.
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Recent advances in semiconductor device fabrication have allowed for the creation of conditions in semiconductor structures where transient electron transport becomes important. Transient effects can dominate electron transport properties when electrons are subject to high electric fields over short distances and time scales. The small size of devices of the order of 0.1 $\mu$m recently achievable, together with a typical device operation voltage, suggest that transient effects are going to govern the behavior of electron transport in semiconductor nanostructure.[1–4] III–V compound semiconductors are expected to be the most interesting group in which to study such transient carrier transport phenomenon. GaAs and InP have been demonstrated to exhibit significant increase of electron drift velocity during their transient transport over their steady-state value.[5,6] In this letter, we report experimental results on the transient electron transport of another technically important semiconductor—$In_xGa_{1-x}As\,(x\cong 0.53)$. The deduced electron drift velocity in $In_xGa_{1-x}As\,(x\cong 0.53)$ has been found to be significantly larger than either GaAs or InP under similar experimental conditions. We attribute this finding to both the smaller electron effective mass and larger $\Gamma$ to $L\,(X)$ energy separations in $In_xGa_{1-x}As$.

The $In_xGa_{1-x}As\,(x\cong 0.53)$-based $p-i-n$ nanostructure studied in this work was grown by molecular beam epitaxy on a (001)-oriented InP substrate. The detailed sample structure is shown in Fig. 1. The $p$-type region is composed of a 100-Å-thick Zn-doped ($\cong 5\times 10^{17}$ cm$^{-3}$) InP layer. The $i$ region is a 1-$\mu$m-thick intrinsic $In_{0.53}Ga_{0.47}As$ layer, which is the active region probed by our Raman scattering experiments. The $n$-type region consists of a 1000-Å-thick Si-doped ($\cong 5\times 10^{17}$ cm$^{-3}$) InP layer. Gold contacts are established on both the $p$ and $n$ sides of the mesa-like $p-i-n$ structure in order to apply an electric field. An opening of 0.25 mm$^2$ is created in the gold layer on the $p$ region of the structure so that light scattering experiments can be carried out. The Zn-doped $p$-type layer and Si-doped $n$-type layer serve as a capacitor and provide a uniform electric field across the active region of the sample.

The excitation source used in this work is a double-jet Styryl 9 dye laser synchronously pumped by the second harmonic output of a cw mode-locked yttrium–aluminum–garnet laser. The ultrafast laser has a pulse width of $\cong$600 fs

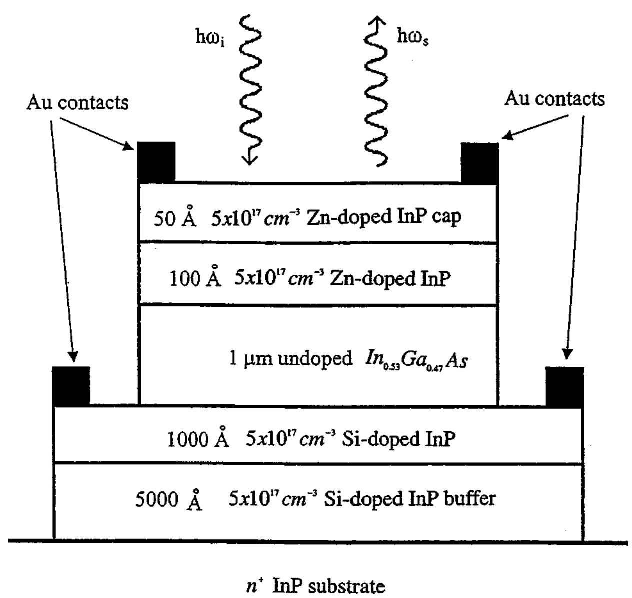


FIG. 1. The $In_{0.53}Ga_{0.47}As$-based $p-i-n$ semiconductor nanostructure used in the transient Raman scattering studies of electron transient transport. The reverse-biased condition is used so that electrons photoinjected inside the 1-$\mu$m-thick undoped $In_{0.53}Ga_{0.47}As$ layer traverse from $p$ region toward $n$ region.

[a]Electronic mail: tsen@asu.edu

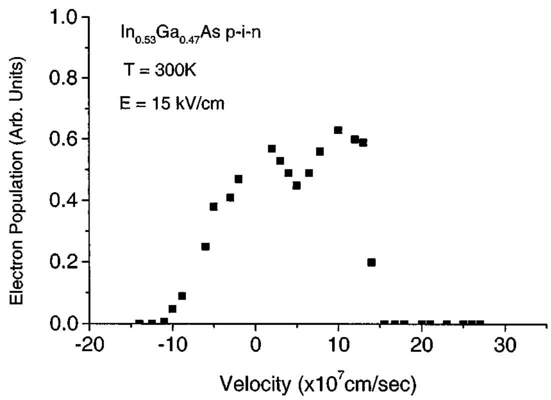


FIG. 2. The measured electron distribution for an $In_{0.53}Ga_{0.47}As$ nanostructure, taken at $T=300$ K, for an electron-hole pair density of $n\cong 5\times 10^{17}$ cm$^{-3}$, and at $E=15$ kV/cm.

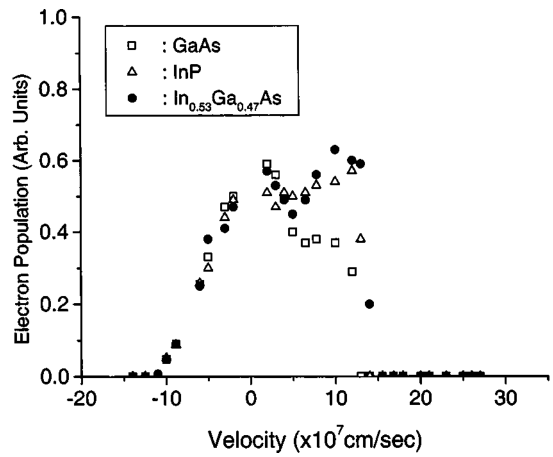


FIG. 3. The measured electron distributions for three semiconductor nanostructures: $In_{0.53}Ga_{0.47}As$-, GaAs-, and InP-based $p-i-n$, taken under the same experimental conditions.

full width at half maximum. In our transient experiments, since the same laser pulse is used to excite and probe nonequilibrium electron transport, the experimental results represent an average over the duration of the laser pulse. The single-particle scattering (SPS) spectra were taken in the $Z(X,Y)\bar{Z}$ scattering configuration where $X=(100)$, $Y=(010)$, $Z=(001)$, so that only the SPS spectra associated with spin-density fluctuations were detected.[7] The backward-scattered Raman signal is collected and analyzed by a standard Raman system consisting of a double spectrometer and a photomultiplier tube. All the data reported here were taken at $T=300$ K.

Once the Raman spectra are measured it is straightforward to convert them to velocity distributions.[4] One can understand this conversion in a simple way as follows: From conservation of energy and momentum in a photon-electron collision process, we obtain

$$\omega=\mathbf{V}\cdot\mathbf{q}+\frac{\hbar q^2}{2m_e^*}, \tag{1}$$

where $\omega\equiv\omega_i-\omega_s$, $\mathbf{q}\equiv\mathbf{k}_i-\mathbf{k}_s$ are angular frequency transfer and wave vector transfer of the incident photon, respectively; $\omega_i$, $\omega_s$ are angular frequencies of incident, scattered photons, respectively; $\mathbf{k}_i$, $\mathbf{k}_s$ are wave vectors of incident and scattered photons, respectively. $\mathbf{V}$ is the electron velocity; $\hbar\equiv h/2\pi$, $h$ is Plank's constant; and $m_e^*$ is the electron effective mass.

Equation (1) states that the angular frequency transfer of incident photon, which is measured in the Raman scattering experiment, is (apart from a constant term) directly proportional to the electron velocity along the direction of wave vector transfer. In other words, it implies that Raman scattering intensity, measured at an angular frequency $\omega$, is proportional to the number of electrons that have a velocity component along the direction of wave vector transfer given by Eq. (1), irrespective of their velocity components perpendicular to $\mathbf{q}$.

Figure 2 shows the measured electron distribution for an $In_{0.53}Ga_{0.47}As$-based $p-i-n$ nanostructure, for an electron-hole pair density of $n\cong 5\times 10^{17}$ cm$^{-3}$, $E=15$ kV/cm, and excitation photon energy of $\hbar\omega=1.43$ eV. The electron distribution has been found to shift to the opposite direction of the applied electric field, as expected. In addition, we have found that the electron distribution is extremely nonequilibrium and has a cutoff velocity at around $1.4\times 10^8$ cm/s. This cutoff velocity is due to the effect of nonparabolicity of the band structure as well as the onset of electron intervalley scattering.

To obtain a better insight into electron transport in $In_{0.53}Ga_{0.47}As$, we have carried out similar Raman measurements for GaAs-based $p-i-n$ and InP-based $p-i-n$ nanoistructures under the same experimental conditions but with the same initial electron excess energy of about $\Delta E\cong 0.65$ eV. These experimental results are shown in Fig. 3. The measured electron drift velocities are $(3.2\pm 0.3)\times 10^7$ cm/s, $(4.0\pm 0.4)\times 10^7$ cm/s, $(5.4\pm 0.5)\times 10^7$ cm/s, for GaAs, InP, and $In_{0.53}Ga_{0.47}As$, respectively. We attribute the significantly higher electron drift velocity found in $In_xGa_{1-x}As$ at $T=300$ K to both the smaller electron effective mass and the larger $\Gamma$ to $L$ ($X$) energy separations in $In_xGa_{1-x}As$.

To understand and interpret our experimental results, we have carried out ensemble Monte Carlo (EMC) simulations[8] of the photoexcitation process in such a $p-i-n$ diode with parameters appropriate to the experimental structure.[9] In the main panel of Fig. 4, we plot the distribution function that is calculated. The peaks are sharper here, as no carrier–carrier interactions have been included (which would broaden all the peaks). An important point is the nonparabolicity that is included in the simulations. Here, we have used a nonparabolicity factor different than the bandgap, and which is estimated from the $16\times 16$ $\mathbf{k}\cdot\mathbf{p}$ theory of Cardona *et al.*,[10,11] which suggests that an 80% mass enhancement at an energy of 0.5 eV above the bottom of the conduction band. Larger values of this nonparabolicity factor move the peak in the distribution to lower values of $V_z$, so that the use of this value is driven by the experimental results. Another parameter is the location of the $L$ valleys (and, similarly, the $X$ valleys) of the conduction band. There is some uncertainty in this, with early work suggesting that the $L$ valley lies no more than 0.5 eV above the conduction band minimum,[12,13] but larger values have been suggested by other work.[14] While the value of this parameter does not affect the peak position of the distribution function, it does affect the average electron velocity that is computed. In the inset to Fig. 4, we plot the average velocity for several values of the $L$ valley posi-

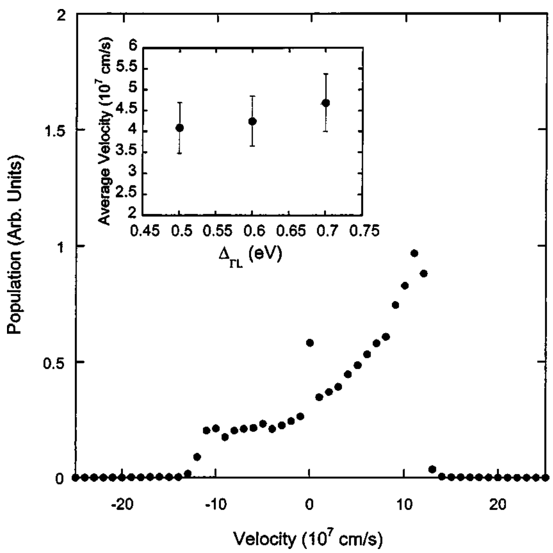


FIG. 4. Electron distribution from EMC simulations for an $In_{0.53}Ga_{0.47}As$-based $p-i-n$ nanostructure. The inset corresponds to electron drift velocity for different values of $\Gamma$-$L$ energy separations in $In_{0.53}Ga_{0.47}As$.

tion (the $X$ valley is kept 0.2 eV higher). Here, the value is averaged over the pulse width of the excitation laser, and the error bars give the variation within this time window. It seems clear that the high velocity measured from the experiment is supported by a valley separation of roughly 0.7 eV.

In conclusion, we have used subpicosecond Raman spectroscopy to study electron transport in an $In_{0.53}Ga_{0.47}As$-based $p-i-n$ nanostructure and have simulated the process with EMC techniques. A large electron drift velocity has been found as compared with other III–V compound semiconductors such as GaAs and InP. We attribute this large electron drift velocity to both the smaller electron effective mass and the larger $\Gamma$ to $L$ $(X)$ energy separations in $In_xGa_{1-x}As$.

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